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ELECTRICAL & COMPUTER ENGINEERING

One-dimensional studies of positive streamer discharges using EMPIRE

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ABSTRACT

Atmospheric streamer discharges are simulated using EMPIRE, a Sandia National Laboratories electromagnetic/electrostatic particle-in-cell (PIC), Direct Simulation Monte Carlo (DSMC) code used for plasma modeling. In particular, this work focuses on the early onset of negative streamers in an electrostatic environment and are studied in detail to demonstrate the capabilities of EMPIRE. The geometry considered is a simple one-dimensional geometry with an electrode gap size of 1 cm and varying applied voltages. A custom gas consisting of only elastic, excitation, and ionization cross section is used to provide collision rates at atmospheric pressure. The simulation is seeded with an initial plasma density near the anode and allowed to propagate towards the cathode via photoionization mechanisms. The role of photoionization length scales on the positive streamer behavior is studied. For example, the photoionization mean free path is varied to observe the influence on streamer velocity and formation. This mean free path is varied from micron scale to the entire gap size (1 cm). These results demonstrate the influence of photoionization length scales on streamer formation behavior and could point to the cause of observed behavior in fully three-dimensional simulations.

BASIC PROBLEM DESCRIPTION

Simple 1D problem is chosen to study atmospheric streamer discharges between two electrodes. Figure below shows the representative geometry where two electrodes are placed some distance apart with gas at atmospheric pressure completely filling the gap. Some of the basic parameters are:

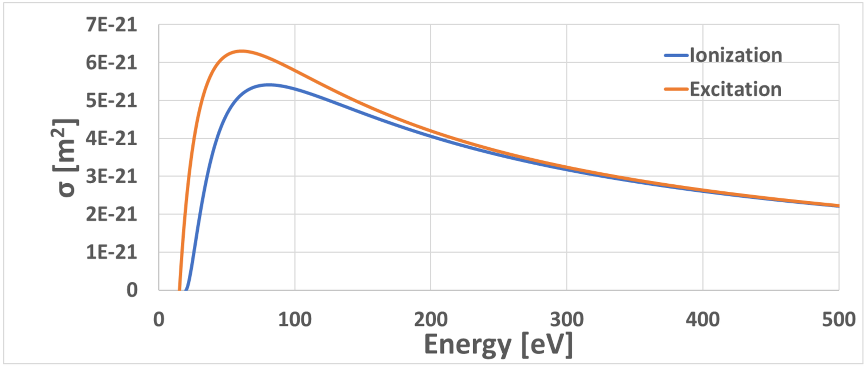
- Electrostatic formulation
- Mesh size = 100 nm
- Time step size = 0.1 ns
- Gap = 10 mm
- Applied voltage = 50 kV
- IC = atmospheric pressure (2.68×10^{25} m^{-3}), temperature (300 K)
- Electro current injected from cathode to start the streamer

GAS MODEL

For the purposes of the simple 1D problem we have developed a pseudo realistic gas with ionization and excitation properties shown in the figure below.

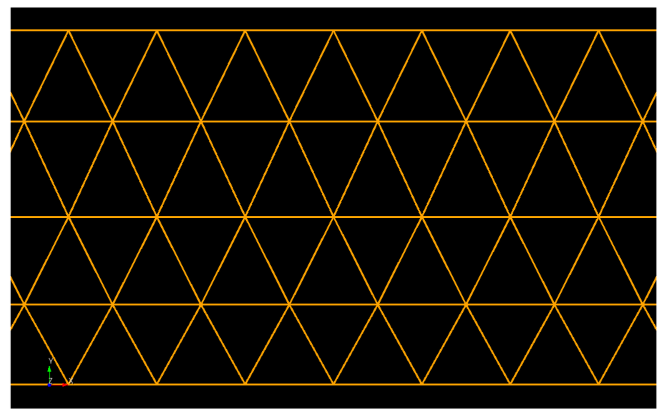
$$\sigma(E_s)\cdot E_s = A\ ln\, E_s + \frac{[B \ln E_s + C(E_s - 1)]}{E_s + D}, where\ E_s = \frac{E_{inc}}{E_{th}}$$

Coeff.	Excit.	Ioniz.
A	0.75	0.75
B	-5.5	-5.0
C	6.0	4.0
D	3.0	0.5
E_{th}	15 eV	20 eV

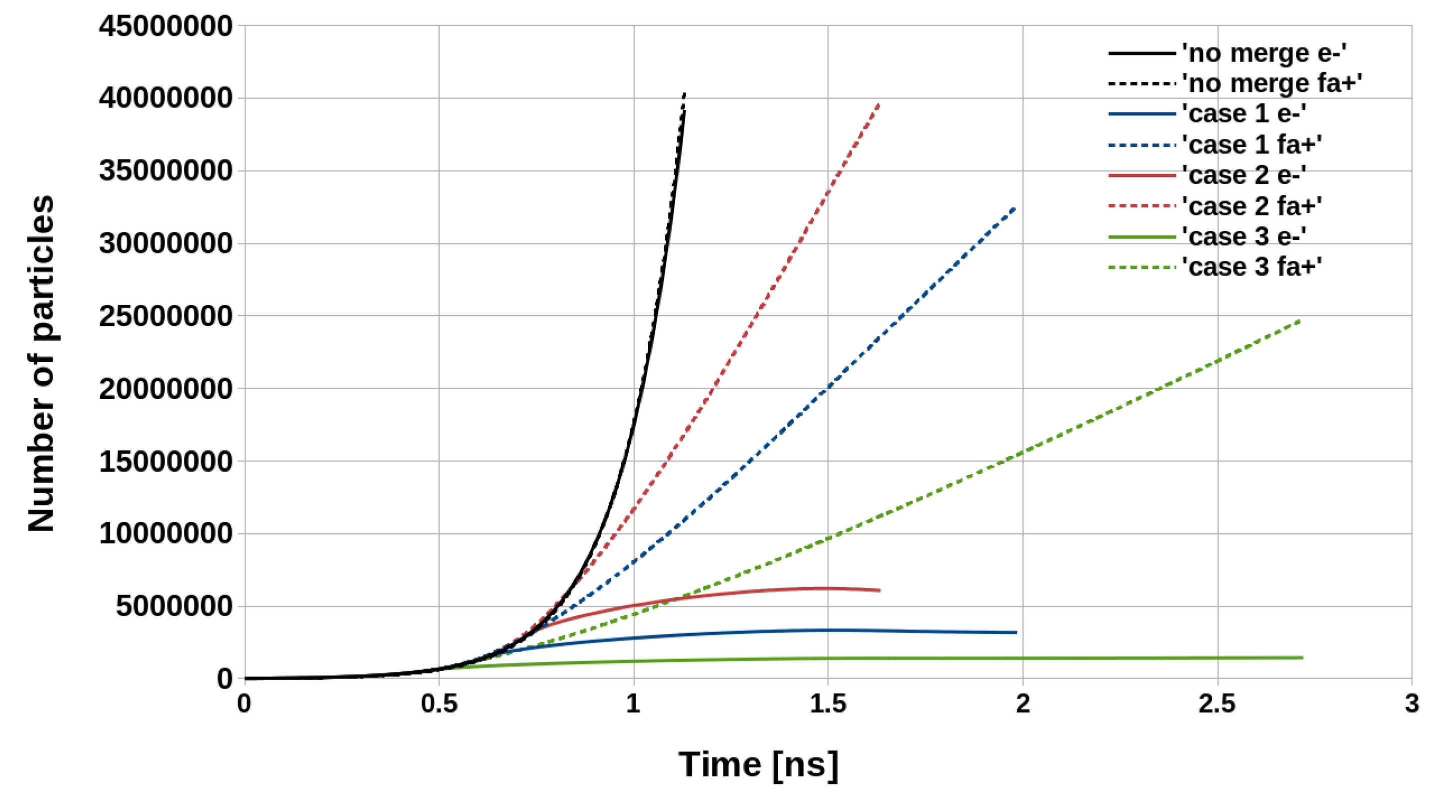


EMPIRE MODEL

EMPIRE-PIC model is based on a mesh shown on the right were left most boundary represents the cathode held at high potential and the right boundary represents the anode held at grounded potential. Upper and lower edges of the mesh are set as periodic boundaries meant to simulate an infinite gas gap.



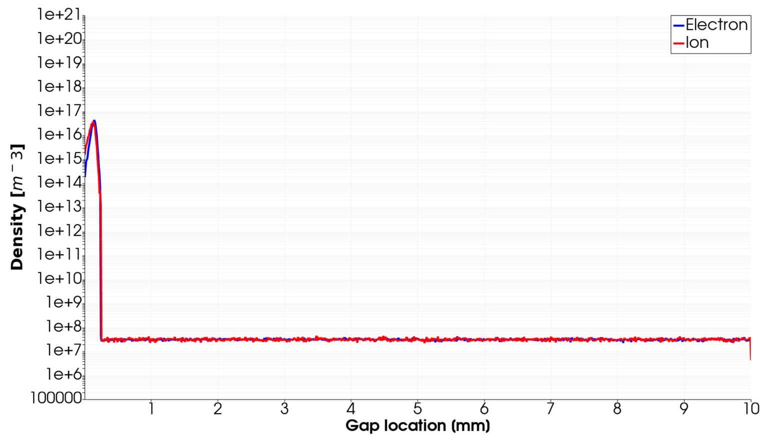
To initiate a streamer discharge a small seed of charged particles is placed throughout the domain and beam-like emission is initiated at the high voltage electrode. In order to control the number of particles injected and to ensure that the simulations is successful without memory errors a particle merge scheme is used. Figure below shows the reduction in overall particle count without any major changes on the outcome of the simulation.



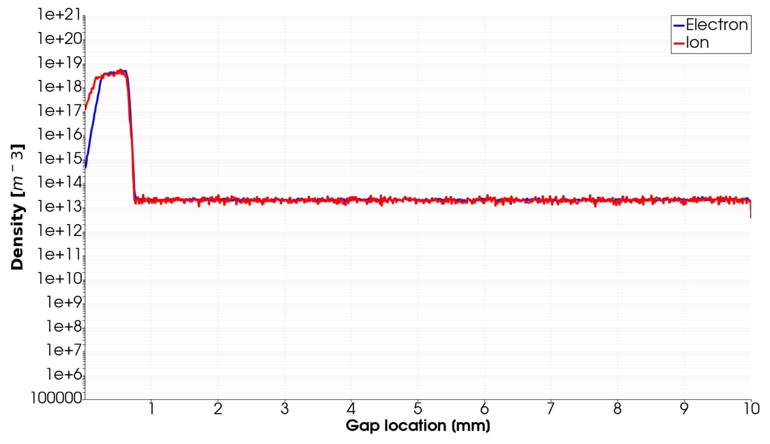
EMPIRE RESULTS

Below are some results showing the evolution of the streamer discharge across the gap. Cathode in the graphs below is at gap location 0, while anode is at gap location 10 mm. What we're showing is the gradual density rise of ionized species within the gap starting at the left-most boundary (cathode) until a uniform density is achieved once the streamer reaches the opposite electrode (anode).

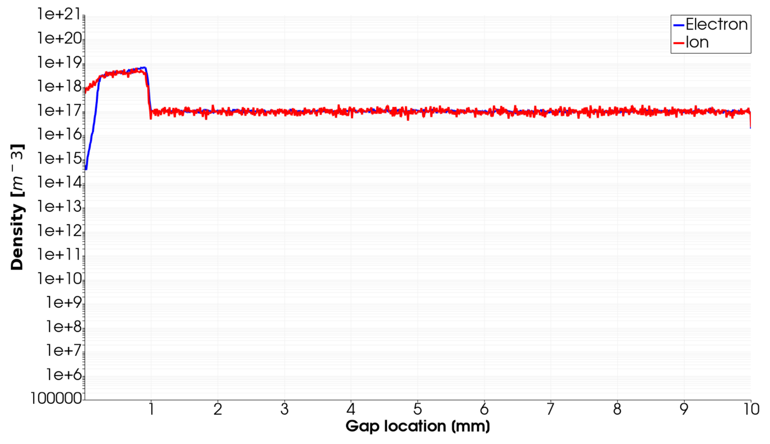
1 ns



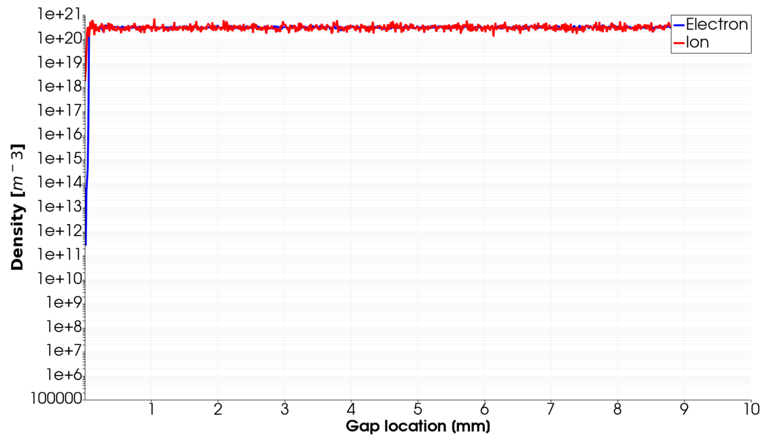
3 ns



4 ns



5 ns



CONCLUSIONS AND REFERENCES

- Developed a one-dimensional PIC model for the atmospheric pressure streamer discharge
- Stabilized the simulation of EMPIRE-PIC to enable simulations of long-duration discharges

FUTURE WORK

- Use a positive streamer within the gap as an initial condition
- Implement photo-ionization of gas
- Develop a model in a hybrid mode which allows PIC and fluid formulations to be used interchangeably.

[1] Bettencourt et. al. EMPIRE-PIC: A Performance Portable Unstructured Particle-in-Cell Code, Communications in Computational Physics Vol. 30, Issue 4 (2021)

[2] Fierro et. al. Radiation transport in kinetic simulations and the influence of photoemission on electron current in self-sustaining discharges J. Phys. D: Appl. Phys. 50 065202 (2017)

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